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BEAM DYNAMICS SIMLATIONS OF THE RF-GUN, PARTICLE SOURCE OF THE CLIC TEST FACILITY

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Abstract

The CERN Linear Collider Test Facility will use a 3 GHz rf-gun with a laser driven photocathode producing a train of intense electron bunches. The characteristics of this beam under the influence of space-charge and wake-fields are evaluated. Simulations are done with the help of TBCI-SF and PRIAM.

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Introduction

The drive linac of the CERN Linear Collider (CLIC) requires very high beam currents [1]. An experimental CLIC Test Facility (CTF) consisting of an rf-gun, a transfer line with a magnetic spectrometer, a post accelerator and a pulse compressor is in preparation [2]. The aim is to study the generation of very short, high-intensity bunches (some ps, more than 10 nC) and of 30 GHz rf-power by deceleration of the bunches in a 30 GHz accelerating structure. The very advanced design of a 1 1/2 cell S-band rf-gun at BNL [3], Fig. 1, and the in-house available 3 GHz power facilities led to the construction of a BNL type gun to speed up the familiarization with the generation of these bunches and their diagnosis.

For beam simulation two programs, PRIAM [4] and TBCI-SF [5], were at our disposal. As both programs showed a good agreement in their results the series of simulations covering a wide range of charges, current densities and field strengths at the cathode were restricted to TBCI-SF runs, cross-checking certain results with PRIAM. For a charge of 1 nC, results obtained at CERN were compared to those calculated at BNL using PARMELA, bringing input conditions carefully into line.

Simulations

The photoelectrons were simulated with an initial parabolic energy distribution centered at 1.5 eV, a constant initial current density over the cathode, and a rectangular or parabolic shape of the bunch in time. As the thermal emittance from the cathode is small compared to the emittance growth during the passage of the particles through the structure, simulations could be restricted to particles with axial velocity at the start. At the outlet of the gun the main attention was paid to the charge transmitted, pulse length, transverse emittance, beam divergence and energy dispersion.

Whereas BNL is concerned with very low emittances, the CTF requires high charges; emittances are of a minor concern provided they fit the admittance of the down stream optics. Results from four case studies are reported here:

a) very high charges,
b) charges, which may be extracted without losses,
c) the nominal charge of 9.4 nC, a reasonable aim for the first experiments,
d) low charge, low emittance for comparison with results obtained at BNL.

The case of very high charges

The upper limit for the charge released from the cathode is Q_i=75nC obtained by assuming maxima for
i) the radius of the laser pulse (r=10mm≡radius of the iris),
ii) the current density ($j=8 A/mm^2$, [6]) and
iii) the pulse length (t=30ps ≈ 30° of rf-phase).

However, simulations for charges higher than 20 nC showed strong particle losses due to emittance growth. The survival rate (charge at outlet Q_f / initial charge Q_i) became a major concern. Fig. 2 presents a typical family of survival curves varying Q_i and the rf-phase Φ. Φ is given with respect to the start of the laser pulse. $Q_{f,max}$=38 nC could be obtained, but this at a sacrifice of emittances, energy dispersion and survival rate.

Charges, extracted without losses

Fig. 2 shows that charges of 20 nC can be extracted without losses. For $0^\circ < \Phi < 50^\circ$ simulations give an emittance growth EG (see table 1 for definition), an energy dispersion dE/E, an angular divergence D, and a pulselength Z (1σ) of

$$\begin{array}{rcccl} 150\,\text{mm mrad} & < & \text{EG} & < & 170\,\text{mm mrad}, \\ 0.7\,\% & < & dE/E & < & 4.4\,\%, \\ 69\,\text{mrad} & < & D & < & 74\,\text{mrad, and} \\ 1.3\,\text{mm} & < & Z & < & 2.3\,\text{mm}, \end{array}$$

provided that a current density $j=8\,A/mm^2$ can be obtained operationally. This seems today still very optimistic.

The nominal case of 9.4 nC

Therefore it was decided to concentrate on a more realistic Q_f which would, nevertheless, give satisfactory performance and would allow to fill the CLIC rf-structure (multi-bunch scheme), achieving the field gradients aimed at. Results of simulations for this case ($Q_i=Q_f$=9.4 nC, r=5 mm, t=30 ps) became the input parameters for the design of the spectrometer and the transfer line downstream. The variation of the most important bunch parameters with Φ is given in fig. 3. Fig. 4 demonstrates bunch rotation in the $\beta\gamma/z$ space. This rotation controlable by Φ may become important for later bunch compression. The typical, highly elongated, tranverse phase space area is shown in fig. 5.

The case low charge (1 nC), low emittance

Both TBCI-SF and PRIAM are Particle-In-Cell codes: they provide a self-consistent solution of Maxwell's equations and particle motion under the Lorentz force law, including space-charge and wake-fields. The main difference between PARMELA, used at BNL, and these programs is that the latter include wake-fields. Therefore it was interesting to compare results obtained at BNL with those at CERN. The most important parameters of the simulations are summarized in table 1. The high ratio (1.34) of the peak field to the field at the cathode for TBCI-SF is due to its restriction to quadratic grids of large mesh size, hampering a good shape approximation. Apart from that fact good agreement of the calculations can be demonstrated. This indicates that in such 3 GHz structures at peak currents of the order of 100 A, space-charge and rf-effects still dominate emittance growth.

Table I : Parameters of a 1 nC bunch (cathode spot radius 3 mm, pulse length 8 ps, field at cathode 100 MV/m)

RF parameters	PARMELA/BNL	TBCI-SF/CERN	PRIAM/CERN	
RF frequency	2856	2855	2859	MHz
frequency (π-mode) - frequency (0-mode)	1.9	1.6	1.7	MHz
Cavity Q	12000	11964		-
Cavity peak power	5.9	6.02		MW
Peak field / field at cathode	1.06	1.34	~1	-
Bunch parameters at the exit of the gun			(RF phase 61 degrees)	
Mean momentum	4.60	4.63	4.65	MeV/c
Energy dispersion (4σ)	2.3	2.7	1.6	%
Angular divergence	36 (2σ)	37 (max.)	38 (max.)	mrad
Emittance growth	22	33	38	mm mrad
Bunch radius	5.3 (2σ)	5.8 (max.)	5.5 (max.)	mm
Bunch length (4σ)	2.84	2.84	2.43	mm

- BNL RF parameters from [3]; BNL beam parameters by H.Kirk (4/30/90);
- emittance growth is calculated for macroparticles (rings) as:
$EG = 2\beta\gamma\sqrt{<r^2><r'^2> - <rr'>^2} = \sqrt{(total\ Emittance)^2 - (Emittance\ at\ cathode)^2}$; $r' = dr/dz$;
- electric field at cathode / peak field in 2nd cell equals 1;

Conclusions

The simulations demonstrate that the CTF particle source without any magnetic confinement can give output charges of the order of 10 to 20 nC, at pulselengths of 30 ps or less, emittances in the range of 100 to 170 mm mrad and energy dispersions of less than 4.4 % (1σ).

Acknowledgements

We would like to thank P.Schuett, T.Weiland and their team for providing the program TBCI-SF, W.-R. Novender and Profi Engineering for providing PROFI, and W.Remmer for the installation of these codes at CERN. Our thanks are given also to G.Le Meur for providing PRIAM. As well we express our thanks for the frequent advice of the authors of the programs and for the PARMELA run done by H.Kirk (BNL) which eased code comparison considerably.

References

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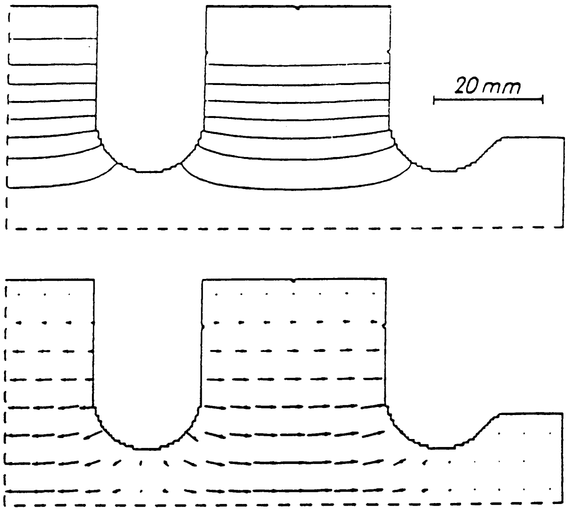

Fig. 1: Field patterns ($H\varphi * r$ = const., E) of the 3 GHz 1 1/2 cell rf-gun oscillating in π-mode; the cathode is located on the left side.

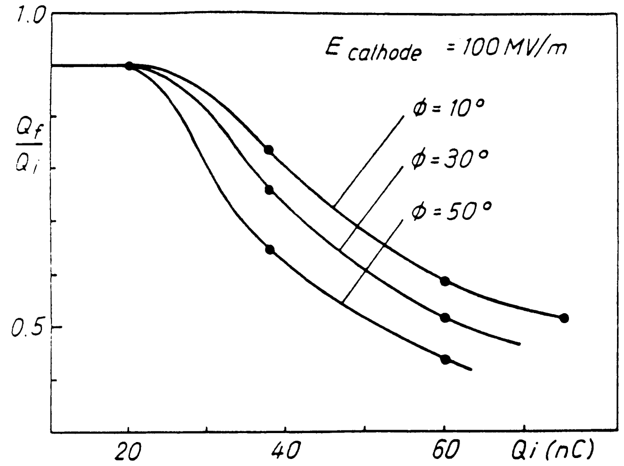

Fig. 2 : The survival rate Q_f/Q_i as function of the initial charge Q_i of the bunch ($t = 30 ps$, $j = 8 A/mm^2$) for different rf-phases.

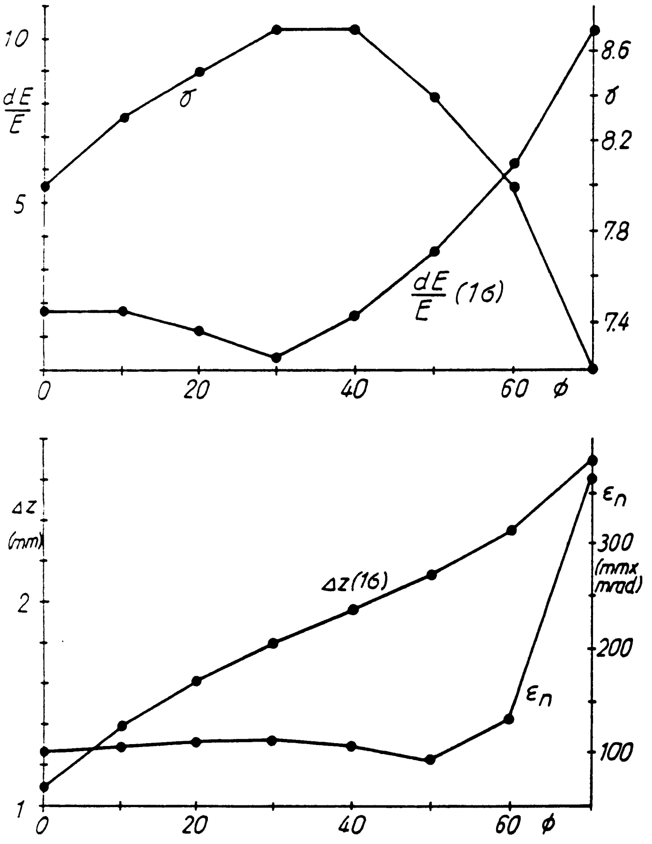

Fig. 3 : Energy, energy dispersion, normalized transverse emittance and bunch length of a 9.4 nC bunch ($r = 5mm$, $t = 30 ps$) as a function of the rf-phase at the laser pulse.

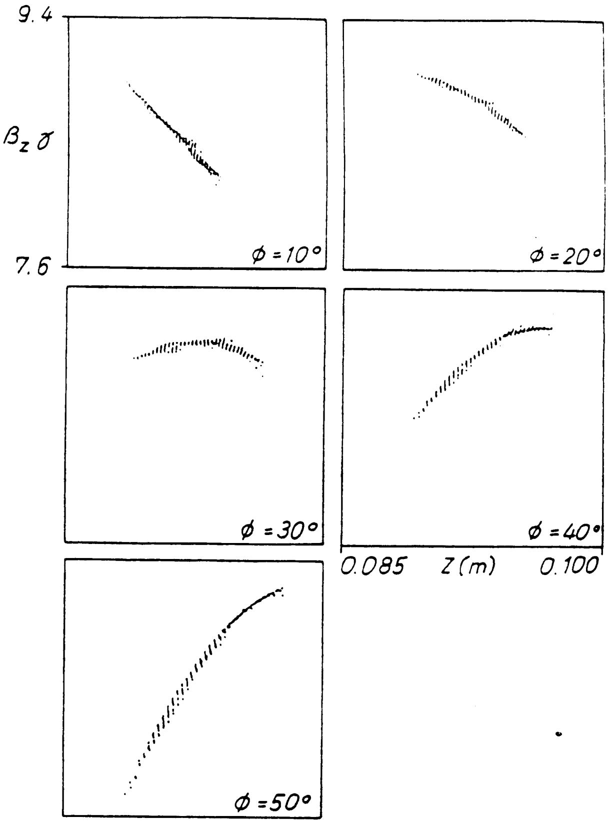

Fig. 4 : Longitudinal phase space diagrams for a 9.4 nC bunch ($r = 5mm$, $t = 30 ps$) at the outlet of the rf-gun. Parameter of the curves is the rf-phase at the laser pulse.

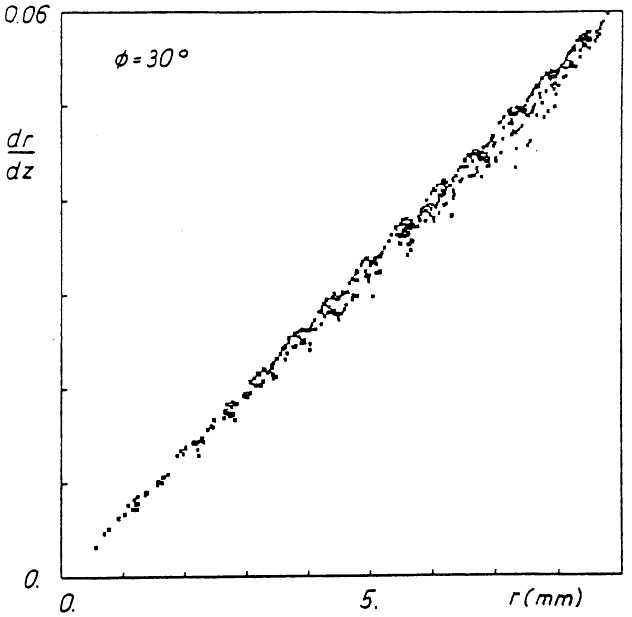

Fig. 5 : Typical transverse phase space diagram for a 9.4 nC bunch ($r = 5mm$, $t = 30 ps$) at the outlet of the gun.